SPIN DEPENDENCE IN ELASTIC SCATTERING IN THE CNI REGION

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The interference of the electromagnetic spin-flip amplitude with a hadronic spin-nonflip amplitude in the elastic scattering of hadrons leads to significant spin dependencies at very low 4-momentum transfer t ($0.001 < |t| < 0.01$ (GeV/c)^2). This kinematical region is known as the Coulomb Nuclear Interference (CNI) region. First results on spin effects in polarized proton–proton elastic scattering in the CNI region at 100 GeV from the 2004 polarized proton run at RHIC are presented. Preliminary results on A_N in the elastic scattering of polarized protons off a carbon target over a wide energy range from 4 GeV to 100 GeV from AGS and RHIC are presented, as well. These results allow us to further investigate the spin dependence in elastic scattering and the mechanisms at work.

In some sense elastic scattering of hadrons is the simplest and the most basic type of nuclear interaction (see Figure 1), yet elastic scattering phenomena have eluded a detailed and satisfactory explanation from general principles for a long time. The formalism for polarized elastic scattering is well developed in terms of five independent helicity amplitudes $\phi_i(t)$ with, however, little understanding of the mechanisms at work. The region of low 4-momentum trasfer t is associated with long distance phenomena, and therefore is in the domain of non-perturbative QCD, where no precise predictions can be made. Several meson exchange models based on Regge phenomenology have been developed to describe the observed data. Naivly one would expect that simple concepts like angular momentum conservation and helicity conservation in the $s-$channel lead to simple and predictable spin *effects*. Most of these models, that otherwise seemed to work, failed to predict the observed spin dependencies.

In this talk I will discuss recent A_N results in pp and pC elastic scattering in the very low t region of $|t| <$ few $\times 10^{-2}(\text{GeV}/c)^2$ from the 2004 polarized proton run at RHIC using internal targets. The analyzing power A_N is defined as the left–right asymmetry of the cross section in the scattering plane normal to the beam or target polarization. A_N arises from the interference between a spin-flip and spin-nonflip amplitude and thus provides basic information on the spin dependence of the interaction.

In high energy pp and pA elastic scattering at very low 4-momentum transfer t, A_N originates from the interference between the real electromagnetic (Coulomb) spin-flip amplitude, which is generated by the proton's anomalous magnetic moment, and the imaginary hadronic (Nuclear) spin-nonflip amplitude (CNI = Coulomb Nuclear Interference). A_N reaches a predicted maximum value of about 4–5 % around a t value of 3×10^{-3} $(\text{GeV}/c)^2$ and decreases with increasing $|t|$.

The existence of a potential hadronic spin-flip amplitude interfering with the electromagnetic spin-nonflip amplitude introduces a deviation in shape and magnitude for A_N calculated with no hadronic spin-flip. [1]. While the former contribution is fully calculable, the latter can be tackled only in Regge inspired phenomenological approaches [2]. Note that the conservation of angular momentum imposes restrictions on the helicity-flip amplitudes in the forward direction (i.e. for $|t| \to 0$) and $\phi_5(t) \propto \sqrt{|t|}$. The hadronic spin-flip amplitude carries important information on the static properties and on the constituent quark structure of the nucleon, since the $|t|$ dependence of this hadronic spin-flip amplitude at small $|t|$ is tightly connected with the structure of hadrons. Within Regge phenomenology, one can probe the long standing issue of the magnitude of the Pomeron spin-flip through the study of A_N in the CNI region. In a quark-diquark picture of the proton the magnitude of the Pomeron spin-flip amplitude can be associated with the diquark separation, the smaller this separation the bigger the effect, suggesting thus that the spin part of the Pomeron probes the smallest distances in the proton.

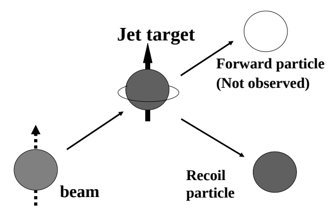

Figure 1. The elastic scattering process: sometime the recoil proton flips its spin yielding to the left - right scattering asymmetry, A_N.

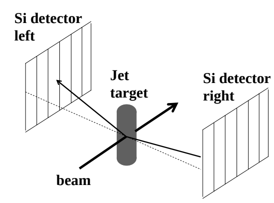

Figure 2. Layout of the pp elastic scattering setup. The atomic beam crosses the RHIC beam from the top.

$p\, p^{\uparrow} \;\rightarrow\; p\, p$

Using internal targets (atomic hydrogen jet target and carbon ribbons) the RHIC accelerator can be operated also in a fixed target mode, with typical energies of $\sqrt{s} = 7 \div 22$ GeV. The main motiviation for studying polarized elastic scattering in the CNI region comes from a need of very precise beam polarization measurements at RHIC. For details on the RHIC polarimeters see D. Svirida talk at this Symposium [3].

Figure 2 shows the schematic layout of the pp elastic scattering experiment. In the CNI region recoil protons from pp elastic scattering emerge close to 90° with respect to the beam direction. In this t region, the elastic process is fully constrained by the recoil particle only, thus the detection of the scattered beam proton is not mandatory. The recoil protons were detected using an array of silicon detectors located at $\sim$ 80 cm from the jet target axis on boths sides of the beam and covered an aziumuthal angle of $\sim 15°$ on each side. These detectors provided energy ($\Delta T_R \leq 60$ keV), polar angle ($\Delta\vartheta_R \sim 1.6$ mrad, horizontal segmentation of the recoil detectors $\sim$ 4 mm) and time of flight (ΔToF $\sim$ 3 ns, from intrinsic resolution and bunch length) measurements of the recoil particles. In the t range of $0.001 < |t| < 0.01$ (GeV/c)^2 the recoil protons were fully absorbed in the recoil detectors. Recoil protons were identified on the basis of the ToF – T_R non-relativistic relation $T_R = \frac{1}{2} M_p(\text{dist}/\text{ToF})^2$ and selected on the basis of the $\vartheta_R - T_R$ relation $T_R \simeq 2M_p\vartheta_R^2$. The estimated background below the elastic peak was less than 5%. For additional information on the experiment, event selections and results see H. Okada talk at this Symposium [4].

The atomic hydrogen beam crossed the RHIC beams from the top with its polarization directed vertically. The state-of-art atomic polarized source delivered polarized protons with a polarization of 0.924 ± 0.018 (the dilution

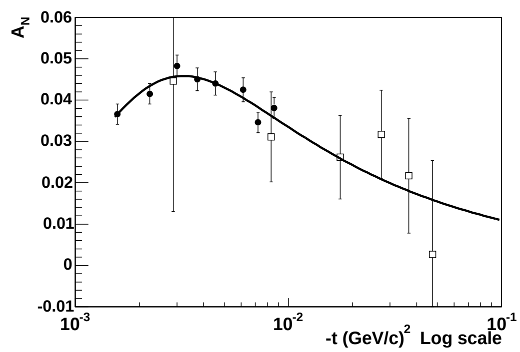

Figure 3. $A_N(t)$ in pp elastic scattering; full circles: this experiment, open squares: E704 at Fermilab [6]. The errors shown are statistical only. For details on the systematic errors see text. The solid line is the CNI – QED prediction with no hadronic spin-flip.

from molecular hydrogen is included in this figure), a density in excess of 10^{12} p/cm^2 in its center, and a FWHM profile of less than 6 mm. The target polarization was reversed each 5 to 10 minutes, thus cancelling most of systematic effects associated with the asymmetry extraction. The jet target, its properties, performace and operation have been discussed in great detail at this Symposium by A. Nass, T. Wise and A. Zelenski [5].

Figure 3 shows the analyzing power $A_N(t)$ for pp elastic scattering in the t range of $0.001 < |t| < 0.01$ $(\mathrm{GeV}/c)^2$ at $\sqrt{s} \simeq 14$ GeV. The displayed errors are statistical only. The two major sources of systematic errors come from the backgrounds and the error on the target polarization: the former is estimated around $\delta A_N^{sys} = 0.0015$ for each measured data point and the latter represents a normalization uncertainty of 2.0%. These data are also compared to a previous, much less precise measurement from the Fermilab E704 experiment at $\sqrt{s} \simeq 20$ GeV [6].

These data are well described by the CNI prediction with no hadronic spin-flip terms ϕ_5^{had} [1]. In Figure 3 the A_N data are fitted with the CNI prediction with a free normalization factor N: χ^2/n d.o.f. $= 5/7$ with $N = 0.98 \pm 0.03$. The interpretation, therefore, does not require additional hadronic spin-flip terms; the sensitivity on ϕ_5^{had} in this t region, however, is limited. A_N data in the larger t range of $0.01 < |t| < 0.03$ $(\mathrm{GeV}/c)^2$ will become soon available. Data on the double spin asymmetry A_{NN} in the same t range will be soon available, as well. That will allow us to perform more extensive studies of the spin dependence in pp elastic scattering and of the mechanisms at work, and draw firmer conclusions on ϕ_5^{had}.

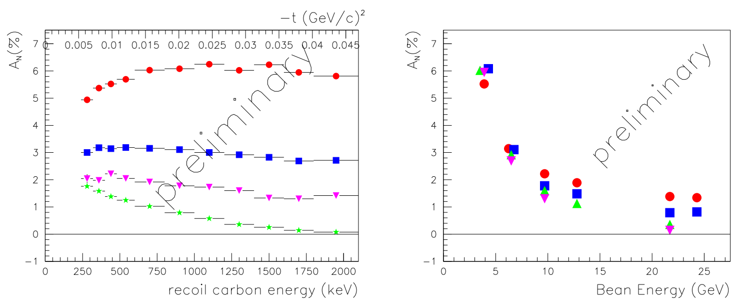

Figure 4. **left:** A_N in % for $pC \to pC$ as function of T_R at 4 different beam energies: starting from top $E_B = 3.9$ GeV, 6.5 GeV, 9.7 GeV, and 21.7 GeV. The displayed errors are statistical only. **right:** A_N as a function of E_B for different intervals of t: full circles $|t| \sim 0.01$ GeV$^2/c^2$, squares $|t| \sim 0.02$ GeV$^2/c^2$, up triangles $|t| \sim 0.03$ GeV$^2/c^2$, down triangles $|t| \sim 0.04$ GeV$^2/c^2$. At larger values of E_B there appears to be a weak or no energy dependence; this behavior is suggestive of the onset of an asymptotic regime.

$p^{\uparrow}\ C \ \rightarrow\ p\ C$

A setup conceptually similar to the one shown in Figure 2 is used for the pC elastic scattering measurements. A carbon ribbon target, as thin as 3.5 μg/cm^2, is inserted from time to time into the AGS and RHIC polarized proton beams. pC elastic scattering events are identified on the basis of the ToF – T_R correlation for the recoil carbon ions. For more details on the setup and analysis see O. Jinnouchi talk at this Symposium [7].

Figure 4 shows the A_N results for pC elastic scattering as a function of the recoil carbon energy T_R ($T_R = |t|/2M_C$) at several incident beam energies from 4 to 22 GeV using the AGS polarized proton beam. At beam energies below 10 GeV a very weak $|t|$ dependence and much larger asymmetries are observed compared to the CNI-type behavior at larger energies. The normalization uncertainty is $\sim$ 10% for the lowest energy data points and increases to $\sim$ 20% for the highest ones. The systematic error, which comes mainly from backgrounds below the elastic pC peak, pileups and electronic noise, is estimated to be $<$ 15% relative.

Figure 5 shows the A_N data as a function of t for pC elastic scattering at 100 GeV using the RHIC polarized proton beam over a wide t interval. For this measurement $P_B = 0.386 \pm 0.033$ as measured with the jet target. The systematic errors, displayed as a band in Figure 5, come mainly from the normalization uncertainty $\Delta P_B/P_B \sim 8.5\%$ and the energy scale in determining the recoil carbon energy T_R. The systematic errors on the *raw* asymmetry measurement alone, however, are very small.

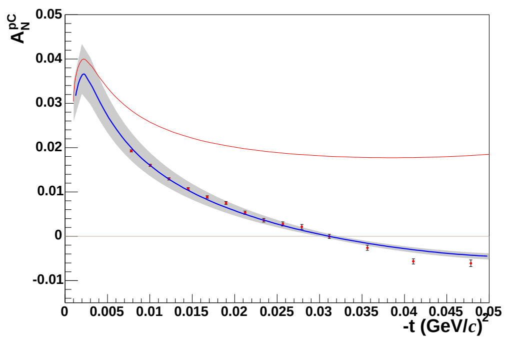

Figure 5. $A_N(t)$ in pC elastic scattering at 100 GeV. The shaded band represents the systematic uncertainties of the measurement. The solid line in the band is a fit to the data including a significant hadronic spin-flip contriubtion (see text). The result is significantly different from the no hadronic spin-flip prediction (top curve).

In Figure 5 these data are fitted with a phenomenological model developed in Ref. [2], which introduces a hadronic spin-flip contribution to A_N via the ω, f_2, and Pomeron trajectories. Contrary to the pp elastic scattering case, these data require a significant hadronic spin-flip contribution with Re $r_5 = 0.051 \pm 0.002$ and Im $r_5 = -0.012 \pm 0.009$. Comprehensive studies and modeling of A_N over the whole energy range should allow us to better understand and disentangle the various contributions to A_N, the rôle of the hadronic spin-flip amplitudes, and the possible onset of asymptotic regimes.

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